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S P E C I F I C A T I O N

METHOD FOR MEASURING DIGGING POSITION

BACKGROUND OF THE INVENTION

[Technical Field of the Invention]

The present invention relates to a method for determining the digging position in a non-open-cut method of excavation and, more particularly, to a method which ensures accuracy in determining positions by lessening the influence of a noise magnetic field of frequency components close to that of the signal magnetic field to be measured.

[Prior Art]

A horizontal drilling method, which is one of the non-open-cut methods of this kind, uses a small-diameter pipe of 100 mm or less across for horizontally digging in the ground, and accordingly, such a precision position determining apparatus as used in an ordinary small-diameter driving method of excavation cannot be placed near a drill. To solve this problem, it is customary in the art to adopt a method in which an AC magnetic field is generated by a coil mounted in the drill head and detected by an above-ground magnetic sensor like a coil to determine the current digging position.

This method is simple and easy, but since the magnetic field by the coil is a dipole magnetic field, it rapidly attenuates with distance from the coil. Hence, this method has a defect of inability to achieve high-reliability determination of the digging position when a power line or similar magnetic noise source is present in the vicinity of the place where to perform the position determination.

SUMMAR OF THE INVENTION

An object of the present invention is to provide a position determination method that permits high-reliability determination of the digging position by detecting on the ground the AC signal magnetic field provided from a coil housed in the drill head even if a noise magnetic field is present which affects the position determination.

To attain the above object, a digging position determining method according to the present invention for non-open-cut excavation, which senses an

AC magnetic field provided from a magnetic field source by a magnetic sensor provided on the ground and calculates the position of the magnetic field source from the magnitude and direction of the sensed magnetic field, said method having a construction characterized in that

In case where in addition to a signal magnetic field generated by said magnetic field source, there exists a noise magnetic field generated by a nearby current,

at lease one of the position of said magnetic field source, the tilt angle of said magnetic field source to the vertical direction and the azimuth angle of its axial direction of said magnetic field source in a horizontal plane is calculated, from a projective component of the magnetic field sensed by said magnetic sensor and projected on a plane or straight line orthogonal to a vector-valued direction of said noise magnetic field.

That is, in 1999 year's investigation and research relating to useful utilization techniques of energy resources: entitled "Research for low-loss energizing techniques in establishment of advanced telecommunication network",(executed by Composite Development System for New Energy Industrial Technique), it is described that external noise magnetic fields, which affects the position determination in the non-open-cut method of excavation, is mostly generated by a current of some kind. In this case, the magnitude of the noise magnetic field varies irregularly with time, but its vector-valued direction is constant at each field sensing position.

The present invention attains its object through the adoption of the following steps (A) and (B).

(A) The direction of the noise magnetic field is detected, and a sensed magnetic field in which the noise magnetic field and a signal magnetic field are mixed is projected on a plane or straight line orthogonal to the direction of the noise magnetic field to obtain a projective component.

Since the projective component is theoretically free from a component

derived from the noise magnetic field, at lease one of the position, azimuth angle and tilt angle of the magnetic field source is calculated so that the magnitude of the projective component (in the case of projection on the straight line) or it magnitude and direction (in the case of projection on the plane) is substantially equal to a theoretically calculated value of a corresponding quantity of a magnetic field generated from a magnetic field source, or ,has a minimum difference between the former and the latter. The sensed magnetic field is obtained by sensing magnetic fields at different positions whose number is determined by how many ones of the position, azimuth angle and tilt angle of the magnetic field source are unknowns and how such unknowns are calculated.

(B) To obtain the noise magnetic field,

a) When the number of noise magnetic fields is virtually one:

· The noise magnetic field is sensed to obtain its direction essentially in the absence of a signal magnetic field.

· When the noise magnetic field has frequency components at frequencies different from that of the signal magnetic field, the frequency components are measured to obtain the direction of the noise magnetic field.

b) When the number of magnetic fields is virtually two:

The frequency components of a first one of the two noise magnetic fields, which are widely spaced from the frequency components of the second noise magnetic field and the signal magnetic field, are measured to obtain a vector direction of the first noise magnetic field, and the frequency components of the second noise magnetic field, which are widely spaced from the frequency components of the first noise magnetic field and the signal magnetic field, are measured to obtain a vector direction of the second noise magnetic field.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the present invention will be clearly understood from the following description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a perspective view explanatory of the placement of a magnetic sensor in the present invention method;

Fig. 2 is a vector diagram explanatory of the principle of measurement according to the present invention method in a case of one noise magnetic field source;

Fig. 3 is a vector diagram explanatory of the principle of measurement according to the present invention method in a case of two noise magnetic field sources;

Fig. 4 is a flowchart illustrating a procedure for obtaining a projective component according to the present invention method in a case of one noise magnetic field source;

Fig. 5 is a flowchart illustrating a procedure for obtaining a projective component according to the present invention method in a case of two noise magnetic field sources;

Fig. 6 is a flowchart illustrating a procedure for obtaining a signal magnetic field in a case of one noise magnetic field;

Fig. 7 is a flowchart illustrating a procedure for obtaining a signal magnetic field in a case of two noise magnetic fields;

Fig. 8 is a flowchart showing a measurement procedure in the present invention method;

Fig. 9 is a flowchart showing a procedure for calculating the position of the signal magnetic field according to the present invention method in a case of one noise magnetic field when the number of unknowns and the number of equations are the same as to each other;

Fig. 10 is a flowchart showing a procedure for calculating the position of the signal magnetic field source according to the present invention method in a case of one noise magnetic field source when the number of equations is larger than the number of unknowns;

Fig. 11 is a flowchart showing a procedure for calculating the position of

the signal magnetic field according to the present invention method in a case of two noise magnetic field sources when the number of unknowns and the number of equations are the same as to each other;

Fig. 12 is a flowchart showing the procedure for calculating the position of the signal magnetic field source according to the present invention method in a case of two noise magnetic field sources when the number of equations is larger than the number of unknowns;

Fig. 13 is a flowchart showing an example of a procedure for obtaining the signal magnetic field through the use of the magnitude of the signal magnetic field vector;

Fig. 14 is a flowchart showing another example of a procedure for obtaining the signal magnetic field through the use of the magnitude of the signal magnetic field vector;

Fig. 15 is a perspective view explanatory of the placement of a magnetic sensor for determining the direction of a noise magnetic field according to the present invention method when a digging head, which is a signal magnetic field source, is distant from the position of measurement;

Fig. 16 is a flowchart showing a procedure for calculating the direction of the noise magnetic field according to the present invention method in a case where the digging head is distance from the position of measurement and the signal magnetic field source stops to generate the magnetic field;

Fig. 17 is a flowchart showing a procedure for calculating the direction of the noise magnetic field according to the present invention method when the signal magnetic field and the noise magnetic field are mixed to each other;

Fig. 18 is a signal frequency spectrum diagram explanatory of how the operation of selecting a frequency for maximizing a frequency spectrum is used in the process for calculating the direction of the noise magnetic field in the flowchart shown in Fig. 13;

Fig. 19 is a flowchart explanatory of a first method by which the flow of

candidate vector calculating process is used in the process for calculating the direction of the noise magnetic field in the flowchart shown in Fig. 17;

Fig. 20 is a flowchart explanatory of a second method by which the flow of candidate vector calculating process is used in the process for calculating the direction of the noise magnetic field in the flowchart shown in Fig. 17;

Fig. 21 is a flowchart explanatory of a method by which the flow of process for evaluating the candidate vector and obtaining the direction of the noise magnetic field is used in the process for calculating the direction of the noise magnetic field in the flowchart shown in Fig. 17;

Fig. 22 is a signal frequency spectrum diagram explanatory of how the operation of selecting a frequency for maximizing a frequency spectrum is used in the process for calculating the direction of the noise magnetic field in the flowchart shown in Fig. 13.

Fig. 23 is a signal waveform diagram explanatory of the operation of specifying a period in which only a noise magnetic field exists through utilization of a fact that the amplitude of the sensed magnetic field signal becomes small during the OFF period of the signal magnetic field that is turned OFF by a predetermined procedure, in the calculation of the direction of the noise magnetic field according to the present invention method;

Fig. 24 is a signal waveform diagram showing instantaneous variations in the amplitude of the sensed magnetic field signal when the signal magnetic field is periodically turned OFF in the calculation of the direction of the noise magnetic field according to the present invention method;

Fig. 25 is a signal waveform diagram showing instantaneous variations in the amplitude of the sensed magnetic field signal when the signal magnetic field is randomly turned OFF in the calculation of the direction of the noise magnetic field according to the present invention method;

Fig. 26 is a flowchart showing a method for calculating the direction of the noise magnetic field according to the present invention in which the signal

magnetic field is turned OFF on the basis of a predetermined sequence, a period during which a particular magnetic field is OFF is specified by a sequence starting at the time when a correlation function between the sequence and the sensed magnetic field becomes maximum, and the direction of the sensed magnetic field in the specified period is regarded as the direction of the noise magnetic field;

Fig. 27 is a flowchart showing a method for calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, and the starting time of a sequence indicating the most likely ON/OFF state of the signal magnetic field is calculated from a plurality of times when a correlation function between the predetermined sequence and the sensed magnetic field becomes maximum;

Fig. 28 is a flowchart showing the method for calculating he direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, the correlation function between the predetermined sequence and the sensed magnetic field is calculated at each of a plurality of time points at which the period of the sequence is equally divided, the magnetic field is projected at each time point to a vector formed by the calculated function, and one of vectors whose variance is minimum is regarded as the direction of the noise magnetic field;

Fig. 29 is a flowchart showing another method for calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, a correlation function between the predetermined sequence and the sensed magnetic field is calculated at each of a plurality of time points at which the period of the sequence is equally divided, the magnetic field is projected at each time point to a vector formed by the calculated function, and one of vectors whose variance is minimum is regarded as the direction of the noise magnetic field;

Fig. 30 is a flowchart showing the method for calculating the direction of

the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, and the starting time of a sequence indicating the most likely ON/OFF state of the signal magnetic field is calculated from a plurality of time points when the correlation function between the predetermined sequence and the sensed magnetic field becomes maximum;

Fig. 31 is a flowchart showing still another method for calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, a correlation function between the predetermined sequence and the sensed magnetic field is calculated at each of a plurality of time points into which the period of the sequence is equally divided, the magnetic field is projected at each time point to a vector formed by the calculated function, and one of vectors whose variance is minimum is regarded as the direction of the noise magnetic field; and

Fig. 32 is a perspective view depicting an example of a magnetic field sensing frame for use in the present invention.

DETAILED DESCRIPTION OF THE INVENTION

As depicted in Fig. 1, in a case where the position of a digging head 2 under the ground surface 1, which is a signal magnetic field source to be sensed, is determined using a magnetic sensor 4 placed on the ground surface 1 at a proper position when a power line or similar magnetic noise source 3, which generates a noise magnetic field, is placed near the digging position to be determined, there are present a signal magnetic field vector H_s provided from the digging head 2 and a noise magnetic field vector H_n from the magnetic noise source 3, such as power line. In this case, the magnetic sensor 4 senses a vector H_m that is a combined version of the signal magnetic field vector H_s and the noise magnetic field vector H_n.

Now, let the noise magnetic field of a position vector $\underline{r}$ and at time $\underline{t}$ be identified as a vector $H_n(r, t)$. On the other hand, let the signal magnetic field

generated by magnetic filed generating means for position sensing be identified as a vector $H_s(r-r_c, \theta_c, t)$. Here, the vector θ_c is an angle of orientation of the magnetic field generating means, which is defined by three angles of rotation in the coordinate system fixed to the ground that is the coordinate system fixed to the magnetic field generating means.

Since the noise magnetic field and the signal magnetic field are both sensed simultaneously and since the noise magnetic field vector $H_n(t, t)$ varies randomly with time, it is impossible to extract only the signal magnetic field vector $H_s(r-r_c, \theta_c, t)$ from the measured magnetic field vector $H_m(r-r_e, \theta_c, t)$ unless statistical properties of the noise magnetic field are known and the noise magnetic field is signal-wise orthogonal to the signal magnetic field. Even if the statistical properties for separating the noise magnetic field from the signal magnetic field are known prior to the determination of the position of the latter, the separation calls for a large amount of data, and hence the conventional scheme is not ever practical. According to the present invention, the direction of a vector $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ is obtained by separated means, and in a coordinate system shown in Fig. 2, a component vector $H_m^P(r-r_c, \theta_c, t)$, projected to a plane vertical to the direction of a vector $e_n(r)$ of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ as shown in Fig. 4 (S1, S2, S3).

$$\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c, \theta_c, t) = \mathbf{H}_m(\mathbf{r}-\mathbf{r}_c, \theta_c, t) - (\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c, \theta_c, t)\cdot\mathbf{e}_n(\mathbf{r}))\mathbf{e}_n(\mathbf{r}). \tag{1}$$

This component does not contain the noise magnetic field for the reason given below. Since

$$\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c, \theta_c, t) = \mathbf{H}_s(\mathbf{r}-\mathbf{r}_c, \theta_c, t) + \mathbf{H}_n(\mathbf{r}, t) = \mathbf{H}_s(\mathbf{r}-\mathbf{r}_c, \theta_c, t) + |\mathbf{H}_n(\mathbf{r}, t)|\mathbf{e}_n(\mathbf{r}). \tag{2}$$

it follows that

$$\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c, \theta_c, t) = \mathbf{H}_s(\mathbf{r}-\mathbf{r}_c, \theta_c, t) - (\mathbf{H}_s(\mathbf{r}-\mathbf{r}_c, \theta_c, t)\cdot\mathbf{e}_n(\mathbf{r}))\mathbf{e}_n(\mathbf{r}). \tag{3}$$

from which it can be seen that the projective component vector $H_m^P(r-r_c, \theta_c, t)$ does not contain the component of the noise magnetic field vector $H_n(r, t)$.

However, the projective component vector $H_m^P(r-r_c, \theta_c, t)$ has lost information of one axis by the projection on a plane vertical to the direction of the

vector $e_n(r)$. That is, since the same projective components are obtained irrespective of the magnitude of a component parallel to the vector $e_n(r)$, two independent components are obtained.

Although any method can be used to obtain the two independent components; it is possible to use such a method as described below.

That one of coordinate axes of a measurement coordinate system C_M (which will be described later on), which is not parallel to the direction $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$, is chosen. Let a unit vector in the direction of the chosen coordinate axis by identified as a vector e_m. A vector product, $e_{p,1}=e_m \times e_n(r)$, of the unit vector and the direction $e_n(r)$ is perpendicular to the direction of the vector $e_n(r)$, and hence it is contained in the plane of projection and is perpendicular to the coordinate axis e_m. Let the magnitude of a vector obtained by projecting the projective component vector $H_m^P(r-r_c, \theta_c, t)$ in the direction of the vector $e_{p,1}$, including the direction of the vector, be represented (S4) by a value of $H_{m,1}^P(r-r_c, \theta_c, t)$. That is,

$$H_{m,1}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t) = \mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot \mathbf{e}_{p,1}. \tag{4}$$

$$\mathbf{e}_{p,1} = \mathbf{e}_m \times \mathbf{e}_n(\mathbf{r}). \tag{5}$$

The next step is to calculate a vector $e_{p,2}$ perpendicular to the directions of the vectors $e_{p,1}$ and $e_n(r)$. The direction of the vector $e_{p,2}$ is also perpendicular to the direction of the vector $e_n(r)$, and hence it is contained in the plane of projection and is perpendicular to the direction of the vector $e_{p,1}$ as well. Letting the projection of the projective component vector $H_m^P(r-r_c, \theta_c, t)$ in this direction be represented by $H_{m,2}^P(r-r_c, \theta_c, t)$, values $H_{m,1}^P(r-r_c, \theta_c, t)e_{p,1}$ and $H_{m,2}^P(r-r_c, \theta_c, t)e_{p,2}$ are two independent vectors into which the projective component vector $H_m^P(r-r_c, \theta_c, t)$ is separated. Here,

$$H_{m,2}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t) = \mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot \mathbf{e}_{p,2}. \tag{6}$$

$$\mathbf{e}_{p,2} = \mathbf{e}_{p,1} \times \mathbf{e}_n(\mathbf{r}) \tag{7}$$

Then, by setting the position vector r_c and angle-of-orientation θ_c of the magnetic field source so that a theoretically calculated magnetic field, $H_c(r-r_c, \theta_c, t)$

generated by the magnetic field source of the position vector r substantially matches with a projective component $H_e^P(r-r_c, \theta_c, t)$ on the same plane as that of the measured magnetic field, it is possible to detect the position and orientation of the magnetic field source.

The above description has been given of a case where the number of noise magnetic fields is virtually one, but when the number of noise magnetic fields is two, letting the direction of two noise magnetic fields $H_{n,j}(r, t)$, where $j = 1, 2$, be represented by vectors $e_{n1}(r)$ and $e_{n2}(r)$, use is made of the projection of the measured magnetic field on a direction vector $e_N(r)=e_{n1}(r)\times e_{n2}(r)$ in the coordinate system of Fig. 3 as depicted in Fig. 5. That is,

$$\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)=\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)-\left(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot\mathbf{e}_N(\mathbf{r})\right)\mathbf{e}_N(\mathbf{r}) \qquad (8)$$

is calculated (S11, S12, S13). In the above

$$\mathbf{e}_N(\mathbf{r})=\mathbf{e}_{n1}(\mathbf{r})\times\mathbf{e}_{n2}(\mathbf{r}) \qquad (9)$$

where the symbol "x" indicates a vector product. In this instance, an independent component in the projective component is one, that is, only the magnitude of the vector.

Now, let the coordinates of the magnetic field source be represented by a vector $r_c(x, y, z)$ and its angle of orientation by a vector $\theta_c(\theta_x, \theta_y, \theta_z)$. In the following description, θ_x, θ_y and θ_z will be referred to as an angle of rotation, a tilt angle and an azimuth, respectively. When the signal magnetic field is axially symmetric, the axis of symmetry is regarded as the x– axis, and the angle of orientation is set to a vector $\theta_c(\theta_y, \theta_z)$.

Further, according to the present invention, it is possible to calculate the magnitude $H_m(r-r_c, \theta_c)$ of each component of the original signal magnetic field vector $H_m(r-r_c, \theta_c, t)$ by synchronous detection of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ through the use of a proper one component in Eq. (1) or (6) that is a projective component.

$$\mathbf{H}_s(\mathbf{r}-\mathbf{r}_c,\ \theta_c)=\left\langle\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)H_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t. \qquad (10)$$

In the above, $H_m^P(r-r_c, \theta_c, t)$ is a proper component of the projective

component given in Eq. (1) or (6).

Fig. 4 shows the case where the number of noise magnetic field sources is essentially one. The processing of Fig. 4 is repeated at each measuring point. In the case of essentially two noise magnetic fields, too, the processing shown in Fig. 5 is repeated at each measuring point as is the case with Fig. 4.

The magnitude $H_m(r-r_c, \theta_c)$ of the original signal magnetic field $H_m(r-r_c, \theta_c, t)$ can be obtained by calculating Eq. (10) after calculating the projective component at each measuring point.. Concretely, the processing depicted in Fig. 6 or 7 is carried out [(S11, S12, S14, S15, S16) or (S11, S12, S14a, S16)].

<u>How to calculate the position and angle of orientation:</u>

(1) <u>Definitions of the coordinate system and the angle of orientation:</u>

A definition will be given first of the coordinate system necessary for the description of the invention.

A coordinate system is set which is fixed to the earth with the z– axis in a vertical direction (upward), which system will hereinafter be referred to as a measuring coordinate system vector C_M. The x– and y– axes are properly set so that they form a right-hand system. For example, they are set in parallel to the direction in which the side of a measuring frame is projected on a horizontal plane.

This has for its object to calculate the coordinate vector $r_e(x, y, z)$ and angle-of orientation vector $\theta_c(\theta_x, \theta_y, \theta_z)$ of the magnetic field source in the coordinate system.

On the other hand, as the coordinate system vector C_c of the magnetic field source, a coordinate system with the axial direction of the magnetic field source as the x axis is set so that the y– and z– axes are horizontal and vertical (upward), respectively, when the magnetic field source is placed horizontally.

The angle-of-orientation vector θ_c of the magnetic field source is defined as the angle of rotation between the measuring coordinate system vector C_M and the coordinate system vector C_c as described below. In the first place, a coordinate system C_{c0} parallel to the measuring coordinate system vector C_M is turned by an

azimuth angle θ_z about the z– axis (in either one of the coordinate system). This coordinate system will be referred to as a coordinate system vector C_{c1}. Next, the coordinate system vector C_{c1} is turned by a tilt angle θ_y about the y– axis of the coordinate system vector C_{c1} itself. This coordinate system will be referred to as a coordinate system vector C_{c2}. Further, the coordinate system vector C_{c2} is turned by an angle of rotation θz about the x– axis of the coordinate system vector C_{c2} itself. The angle-of-orientation vector θ_c is determined so that the resulting coordinate system becomes the coordinate system vector C_c.

(2) <u>Explanation of independent measurands and unknowns:</u>

When the number of noise magnetic fields is essentially one, the measurement of the magnetic field at one place will provide two independent measurands. When the number of noise magnetic fields is essentially two, the measurement of the magnetic field at one place will provide one independent measurand. Further, in case of obtaining components of the original signal magnetic field by synchronous detection, the measurement of the magnetic field at one place will provide three independent measurands. On the other hand, three coordinate components of the coordinate vector $r_c(x, y, z)$ of the magnetic field source are unknowns. The azimuth angle θ_z is not obtainable without a different criterion such as the direction of the earth magnetism, and hence it is also an unknown unless the digging head is provided with a direction sensor. When the digging head is made of a magnetic material, or when a buried steel pipe or similar magnetic body lies near the digging head, an accurate direction cannot be obtained even if the direction sensor is provided; hence, the azimuth angle θ_z is an unknown in many cases. The tilt angle θ_y can easily be detected by a tilt angle sensor that detects the vertical direction, and hence it is known in many cases. The same is true of the angle of rotation θ_x. In particular, when the signal magnetic field is axially symmetric, if the axis of symmetry is regarded as the x– axis, the angle of rotation θ_x becomes meaningless and hence can be ignored.

At any rate, measured magnetic fields need only to be obtained at different

positions so that independent measurands larger in number than unknowns.

Arrangement of the measuring system:

For example, as shown in Fig. 1, magnetic fields are measured using a required number of three-axis magnetic sensors disposed on the ground so that their relative positions are known. Since the direction of the noise magnetic field changes for each position of measurement, it is necessary to perform for each position the step (S21) for detecting the position of the noise magnetic field and the step (S22) for calculating the projective component of the measured magnetic field as shown in Fig. 8 that is a flowchart of the procedure for position determination by the present invention. In case of calculating the component of the original signal magnetic field by synchronous detection, the processing therefor (in a specified step) needs to be carried out for each position.

Flow of measurement processing:

A detailed description will be given of the detection (S21) of the direction of the noise magnetic field, the calculation (S23) of the position of the signal magnetic field source through the use of the projective component and the calculation of the position f of the signal magnetic field through the use of the signal magnetic field component.

[EMBODIMENTS]

Embodiment in the case of virtually one noise magnetic field:

In case of using the projective component, when the number of unknowns is $N_U(\geq 1)$ and the number of noise magnetic fields is virtually one, the projective component vector $H_m^P(r-r_c, \theta_c, t)$ expressed by Eq. (1) is calculated from magnetic vectors $H_m(r-r_c, \theta_c, t)$ measured at $N_U/2$ or more different positions, and the position vector r_c and the angle-of-orientation vector θ_c are determined (S31) as depicted in Fig. 9 so that a projective component vector at each magnetic field sensing point is essentially equal to the projective component vector $H_e^P(r-r_c, \theta_c, t)$ of a theoretically calculated magnetic field of the projective component at each position of measurement, by which it is possible to detect (S32) the position and

orientation of the magnetic field source.

In case of using the magnitude of the signal magnetic field synchronously detected by the projective component, the magnetic field is measured at $N_U/3$ or more different positions. When the number $N_U(\geq 1)$ of unknowns is even, the number of unknowns and the number of independent measurands can be made equal to each other; if setting magnetic field vector $H_m(r-r_c, \theta_c, t)$ is measured at positions $N_m=N_U/2$, a N_U number of such equations as given below need only to be solved.

$$\langle H_{m,q}^{P}(r_k - r_c, \theta_c, t)\rangle_t - H_{e,q}^{P}(r_k - r_c, \theta_c) = 0,\ k = 1, \ldots, N_m;\ q = 1, 2. \quad (11)$$

where q = 1, 2 and represents two directions parallel to the plane of projection but parallel to each other (S33). Accordingly, $H_{m,q}^{P}(r-r_c, \theta_c, t)$ and $H_{e,q}^{P}(r-r_c, \theta_c, t)$, where q = 1, 2, are the magnitudes of q-direction components of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ and the theoretical calculated magnetic field vector $H_e(r-r_c, \theta_c, t)$, respectively. Let it be assumed that the vector θ_c represents any one of θ_x, θ_y, θ_z, (θ_y, θ_z), (θ_z, θ_x), (θ_x, θ_y), $(\theta_x, \theta_y, \theta_z)$ and ϕ and that the vector r_c represents any one of x, y, z, (y, z), (z, x), (x, y), (x, y, z) and ϕ, where ϕ represents an empty set.

For example, when unknowns are the position vector $r_c(x, y, z)$ and azimuth angle θ_z of the magnetic field source, the magnetic field is to be measured at two different positions and four equations such as given below are solved, by which it is possible to obtain (S34) the position vector $r_c(x, y, z)$ and azimuth angle θ_z of the magnetic field source.

$$\langle H_{m,q}^{P}(r_k - r_c, \theta_z, t)\rangle_t - H_{e,q}^{P}(r_k - r_c, \theta_z) = 0,\ k = 1, 2;\ q = 1, 2. \quad (12)$$

In the above, $<.>_t$ represents a time average.

As depicted in Fig. 10, when the magnetic field is measured at N_m ($>N_U/2$) different places more than $N_U/2$ in excess of the number N_U of unknowns, since a larger number of independent measurands than the number of unknowns can be obtained (S41, S42, S43), the position $r_c(e, y, z)$ and the angle of orientation θ_z are calculated which provide

$$\min_{\mathbf{r}_c,\ \theta_c}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\left\langle H_{m,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_{c,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \qquad (13)$$

where $<.>_t$ represents the time average and $\min_{\mathbf{r}_c,\theta_z}\{.\}$ means that vectors $\mathbf{r}_c$ and θ_c are changed to obtain vectors $\mathbf{r}_c$ and θ_c that minimize the contents in $\{.\}$. Further, a symbol $w_{k,q}$ indicates weighting. The Eq. (13) can be replaced with the following equations (S44).

$$\min_{\mathbf{r}_c,\ \theta_c}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\sqrt{\left\langle\left|H_{m,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right|^2\right\rangle_t} - H_{c,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \qquad (14)$$

$$\min_{\mathbf{r}_c,\ \theta_z}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\left\langle H_{m,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_{c,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_z)\right|^2\right\}. \qquad (15)$$

$$\min_{\mathbf{r}_c,\ \theta_z}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\sqrt{\left\langle\left|H_{m,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right|^2\right\rangle_t} - H_{c,q}^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_z)\right|^2\right\}. \qquad (16)$$

Assume that vectors $\mathbf{r}_c$ and θ_c in Eqs. (13), (14), (15) and (16) have the same meaning as in the case of Eq. (11).

In the above description it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal having passed through a band pass filter that permits the passage therethrough of only components close to the frequency of the signal magnetic field or a wide-band signal that is inhibited from the passage through the band pass filter, but the use of the signal having passed through the band pass filter increases the possibility of determining the position of the magnetic field with high reliability.

(Embodiment in the case of essentially two noise magnetic fields)

When the number of unknowns is N_U (≥ 1) and the number of noise magnetic fields is virtually two, the projective component vector $H_m^P(r-r_c, \theta_c, t)$ expressed by Eq. (4) is calculated from magnetic vectors $H_m(r-r_c, \theta_c, t)$ measured at $N_U/2$ or more different positions, and the position vector $\mathbf{r}_c$ and the angle-of-orientation vector θ_c are determined (S51, S52) as depicted in Fig. 11 so that the above-mentioned projective component vector obtained at each position of

measurement essentially matches with the projective component vector $H_e^P(r-r_c, \theta_c, t)$ of a theoretically calculated magnetic field at each position of measurement, by which it is possible to detect (S53) the position and orientation of the magnetic field source.

In this case, the number N_U (≥ 1) of unknowns and the number of independent measurands can be made to be equal to each other without fail; the magnetic field vector $H_m(r-r_c, \theta_c, t)$ is measured at different positions of the same number as that N_U number of unknowns, and N_U number of such equations given below need only to be solved.

$$\left\langle H_m^P(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_e^P(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c) = 0,\ k = 1,\ \ldots,N_U. \tag{17}$$

In this case, symbols $H_m^P(r-r_c, \theta_c, t)$ and $H_e^P(r-r_c, \theta_c, t)$ are the respective magnitudes of the projective component vector $H_m^P(r-r_c, \theta_c, t)$ and the vector $H_e^P(r-r_c, \theta_c, t)$ of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ and the theoretical calculated magnetic field vector $H_e(r-r_c, \theta_c, t)$. Let it be assumed that the vector θ_c represents any one of θ_x, θ_y, θ_z, (θ_y, θ_z), (θ_z, θ_x), (θ_x, θ_y), $(\theta_x, \theta_y, \theta_z)$ and ϕ and that the vector r_c represents any one of x, y, z, (y, z), (z, x), (x, y), (x, y, z) and ϕ, where ϕ represents an empty set.

For example, when unknowns are the position vector $r_c(x, y, z)$, azimuth angle θ_z and tilt angle θ_y of the magnetic field source, the magnetic field is to be measured at five different positions and four such equations given below are solved, by which it is possible to obtain the position vector $r_c(x, y, z)$, azimuth angle θ_z and tilt angle θ_y of the magnetic field source.

$$\left\langle H_m^P(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_e^P(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c) = 0,\ k = 1,\ \ldots,5. \tag{18}$$

In the above, $<.>_t$ represents a time average. And the vector $\theta_c = \theta_c(\theta_y, \theta_z)$.

As depicted in Fig. 12, when the magnetic field is measured at N_m ($>N_U$) different places more than N_U in excess of the number N_U of unknowns, since a larger number of independent measurands than the number of unknowns can be obtained (S61, S62), the position $r_c(e, y, z)$ and the angle of orientation θ_z are calculated which provide

$$\min_{\mathbf{r}_c,\ \theta_c}\left\{\sum_{k=1}^{N_m} w_k \left|\left\langle H_m^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_c^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \qquad (19)$$

where $<.>_t$ represents the time average and $\min\limits_{r_c,\theta_z}\{\,.\}$ means that vectors r_c and θ_c are changed to obtain r_c and θ_c that minimize the contents in { . }. Further, a symbol $w_{k,q}$ indicates weighting. The Eq. (19) can be replaced with the following equations (S63).

$$\min_{\mathbf{r}_c,\ \theta_c}\left\{\sum_{k=1}^{N_m} w_k \left|\sqrt{\left\langle \left|H_m^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right|^2\right\rangle_t} - H_c^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \qquad (20)$$

$$\min_{\mathbf{r}_c,\ \theta_z}\left\{\sum_{k=1}^{N_m} w_k \left|\left\langle H_m^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_c^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|^2\right\}. \qquad (21)$$

$$\min_{\mathbf{r}_c,\ \theta_z}\left\{\sum_{k=1}^{N_m} w_k \left|\sqrt{\left\langle \left|H_m^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right|^2\right\rangle_t} - H_c^{P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|^2\right\}. \qquad (22)$$

Assume that r_c and θ_c in Eqs. (19), (20), (21) and (22) have the same meaning as in the case of Eq. (16).

In the above description, it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal having passed through a band pass filter that permits the passage therethrough of only components close to the frequency of the signal magnetic field, or a wide-band signal that is inhibited from the passage through the band pass filter, but the use of the signal having passed through the band pass filter increases the possibility of determining the position of the magnetic field with high reliability.

Further, in case of using the signal magnetic field component obtained by synchronous detection, the direction of the noise magnetic field is determined and is used to obtain the projective magnetic field; and the subsequent processing is common to the cases of one and two noise magnetic fields. The projective component vectors $H_m^P(r-r_c, \theta_c, t)$ at respective places are calculated from magnetic field vectors $H_m(r-r_c, \theta_c, t)$ measured at $N_U/3$ or more different places, and a proper one of the calculated vectors is used as a reference signal to perform

synchronous detection of the measured magnetic field vectors $H_m(r-r_c, \theta_c, t)$, thereby obtaining the magnitude $H_s(r-r_c, \theta_c)$ of the original signal magnetic field component. By determining the position vector r_c and the angle-of-orientation vector θ_c of the magnetic field source so that the magnitude of the original signal magnetic field component and the magnitude $H_c(r-r_c, \theta_c)$ of the theoretical signal component are equal to each other, it is possible to detect the position and orientation of the magnetic field source.

When the number N_U (≥ 1) of unknowns is a multiple of 3, the number of unknowns and the number of independent measurands can be made to be equal to each other; if the magnetic field vector $H_m(r-r_c, \theta_c, t)$ is measured at positions $N_m=N_m/N_U/3$, N_U number of such equations as given below need only to be solved.

$$\mathbf{H}_s(\mathbf{r}_k - \mathbf{r}_c, \theta_c) - \mathbf{H}_c(\mathbf{r}_k - \mathbf{r}_c, \theta_c) = 0,\ k = 1, \ldots, N_m. \qquad (23)$$

Fig. 13 shows the flow of processing (S61, S62, S65). Here, $H_s(r-r_c, \theta_c)$ and $H_c(r-r_c, \theta_c, t)$ are the signal magnetic field calculated from the measured magnetic field vectors $H_m(r-r_c, \theta_c, t)$ and the magnitude of the theoretical calculated magnetic field vector, respectively. The magnitude $H_s(r-r_c, \theta_c)$ of the signal magnetic field vector is an averaged quantity as already explained. Let it be assumed that the vector θ_c represents any one of θ_x, θ_y, θ_z, (θ_y, θ_z), (θ_z, θ_x), (θ_x, θ_y), $(\theta_x, \theta_y, \theta_z)$ and ϕ and that the vector r_c represents any one of x, y, z, (y, z), (z, x), (x, y), (x, y, z) and ϕ, where ϕ represents an empty set.

For example, when an unknown is the position vector $r_c(x, y, z)$ of the magnetic field source, the magnetic field is to be measured at one place and three such equations as given below are solved, by which it is possible to obtain the position vector $r_c(x, y, z)$ and azimuth angle θ_z of the magnetic field source.

$$\mathbf{H}_s(\mathbf{r} - \mathbf{r}_c) - \mathbf{H}_c(\mathbf{r} - \mathbf{r}_c) = 0. \qquad (24)$$

The vector $\underline{r}$ is the vector of the position of measurement.

When the magnetic field is measured at N_m ($>N_U/2$) different places more than N_U in excess of the number N_U of unknowns, since a larger number of independent measurands than the number of unknowns can be obtained, the

position $r_c(e, y, z)$ and the angle of orientation θ_z are calculated which provide

$$\min_{r_c,\ \theta_c}\left\{\sum_{k=1}^{N_m} w_k \left|\mathbf{H}_s(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c) - \mathbf{H}_c(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c)\right|\right\}. \qquad (25)$$

where $\min_{r_c,\theta_z}\{\,.\}$ means that vectors r_c and θ_c are changed to obtain vectors r_c and θ_c that minimize the contents in $\{\ .\ \}$. Further, a symbol $w_{k,q}$ indicates weighting. The Eq. (25) can be replaced with the following equations.

$$\min_{r_c,\ \theta_c}\left\{\sum_{k=1}^{N_m} w_{k,}\left(\left\|\mathbf{H}_s(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c)\right\| - \left\|\mathbf{H}_c(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c)\right\|\right)^2\right\}. \qquad (26)$$

$$\min_{r_c,\ \theta_z}\left\{\sum_{k=1}^{N_m} w_k \left|\mathbf{H}_s(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c) - \mathbf{H}_c(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c)\right|^2\right\}. \qquad (27)$$

Fig. 14 shows the flow of processing (S61, S64, S66).

A description will be given below of how to determine the direction of the noise magnetic field in the two embodiments described above.

(How to determine the direction of the noise magnetic field in the case of virtually one noise magnetic field)

<u>(First method)</u>

The first method for determining the direction of the noise magnetic field is a method where, in case of no signal magnetic field, a noise magnetic field is measured through the use of the same measuring system as that for measuring the signal magnetic field. This situation is such as shown in Fig. 15 in which the detection of the digging position is disturbed by a noise magnetic field source lying in the vicinity of the digging route. Another case is that where the signal magnetic field source is equipped with a function of receiving a command sent, for example, from the ground by some means and responsive to the command to stop the generation of the signal magnetic field.

In this instance, as depicted in Fig. 16, letting the measured magnetic field be represented by a vector $H_m(r-r_c, \theta_c, t)$, since this is essentially a noise magnetic field vector $H_n(r, t)$ as shown at a step (S71), an average value of its absolute values

can be used (S72) to calculate a direction vector, $e_n(r)=e_{n,x}(r), e_{n,y}(r), e_{n,z}(r))$, of the noise magnetic field as follows:

$$e_{n,\alpha}(\mathbf{r})=\frac{\left\langle\left|H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right|\right\rangle_t}{\sqrt{\sum_{\alpha=x,y,z}\left\langle\left|H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right|\right\rangle^2}},\quad \alpha=x,\ y,\ z. \tag{28}$$

Alternatively, a root-mean-square value of the above absolute values can be used to determine the direction of the noise magnetic field by

$$e_{n,\alpha}(\mathbf{r})=\frac{\sqrt{\left\langle\left(H_{m,\alpha}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right)^2\right\rangle_t}}{\sqrt{\sum_{\alpha=x,y,z}\left\langle\left(H_{m,\alpha}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right)^2\right\rangle_t}},\quad \alpha=x,\ y,\ z. \tag{29}$$

In this case, a symbol $H_{m,\alpha}(r-r_c, \theta_c, t)$ is an α component of the measured magnetic field (the noise magnetic field), and α is any one of x, y and z.

In the above description it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal having passed through a band pass filter that permits the passage therethrough of only components close to the frequency of the signal magnetic field or a wide-band signal that is inhibited from the passage through the band pass filter, but the use of the signal having passed through the band pass filter increases the possibility of determining the position of the magnetic field with high reliability.

<u>(Second method)</u>

<u>Step 1</u>

As shown in Fig. 17, at first , the frequency spectrum $H_m(\omega)$ of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is calculated (S81, S82, S83) by the following equation.

$$\mathbf{H}_m(\omega)=\mathrm{F}\left(\mathbf{H}_m(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right) \tag{30}$$

In this case, a symbol F(.) represents a Fourier transform; the three components x, y and z of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ are each Fourier transformed. In practice, the above-mentioned frequency spectrum can be calculated by FFT (fast Fourier transform) or the like of sampled values of the

measured magnetic field vector $H_m(r-r_c, \theta_c, t)$.

Step 2

Next, an angular frequency ω_i, where $i = 1, 2, \ldots, N_s$, of a large-amplitude component, such as a line spectrum, is selected (S84) from the absolute value $|H_m(\omega)|$ of the frequency spectrum. For the component of each angular frequency ω_i, where $i = 1, 2, \ldots, N_{ns}$, a candidate unit vector $e_n(r, \omega_i)$, where $i = 1, 2, \ldots, N_{ns}$, of the direction of the noise magnetic field, is calculated (S85) by the method (1) or (2) described below.

(1) The absolute values of the Fourier-transformed x, y, and z components of the angular frequency concerned are used to calculate the candidate unit vector $e_n(r, \omega_i)$, where $i = 1, 2, \ldots, N_{ns}$, of the direction of the noise magnetic field, by the following procedures:

$$\mathbf{e}_n(\mathbf{r}, \omega_i) = \frac{\left(\left|\mathrm{H}_{m,x}(\omega_i)\right| \ \left|\mathrm{H}_{m,x}(\omega_i)\right| \ \left|\mathrm{H}_{m,x}(\omega_i)\right|\right)}{\sqrt{\sum_{\alpha=x,y,z} \left|\mathrm{H}_{m,\alpha}(\omega_i)\right|^2}}, \quad i = 1, \ldots, N_{ns}. \tag{31}$$

where $H_{m,\alpha}(\omega_i)$, where $\alpha = x, y, z$ and $i = 1, 2, \ldots, N_{ns}$, is a ω_i component by the Fourier transform of the α component of the measured magnetic field.

(2) A narrow-band filter is formed whose pass band uses, as the center frequency, the angular frequency ω_i, where $i = 1, 2, \ldots, N_{ns}$, and the same method as by Eq. (21) or (22) is used to calculate the candidate unit vector $e_n(r, \omega_i)$, where $i = 1, 2, \ldots, N_{ns}$. That is, the candidate unit vector $e_n(r, \omega_i) = (e_{n,x}(r), e_{n,y}(r), e_{n,z}(r))$, where $i = 1, 2, \ldots, N_{ns}$, is calculated by

$$e_{n,\alpha}(\mathbf{r}, \omega_i) = \frac{\left\langle \left| H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c, \theta_c, \omega_i, t) \right| \right\rangle_t}{\sqrt{\sum_{\alpha=x,y,z} \left\langle \left| H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c, \theta_c, \omega_i, t) \right| \right\rangle^2}}, \quad \alpha = x, y, z;\ i = 1, \ldots, N_{ns}. \tag{32}$$

or by

$$e_{n,\alpha}(\mathbf{r}, \omega_i) = \frac{\sqrt{\left\langle \left(H_{m,x}(\mathbf{r}_k-\mathbf{r}_c, \theta_c, \omega_i, t) \right)^2 \right\rangle_t}}{\sqrt{\sum_{\alpha=x,y,z} \left\langle \left(H_{m,\alpha}(\mathbf{r}_k-\mathbf{r}_c, \theta_c, \omega_i, t) \right)^2 \right\rangle_t}}, \quad \alpha = x, y, z;\ i = 1, \ldots, N_{ns}. \tag{33}$$

Step 3

The candidate unit vector $e_n(r, \omega_i) = (e_{n,x}(r), e_{n,y}(r), e_{n,z}(r))$, where $i = 1, 2, \ldots, N_{ns}$, is considered as the direction vector $e_n(r)$ of the noise magnetic field, and for each angular frequency ω_i, where $i = 1, 2, \ldots, N_{ns}$, the same method as by Eq. (1) is used to calculate a projective component vector $H_m^P(r - r_c, \theta_c, \omega_i, t)$.

$$\mathbf{H}_m^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_c, \theta_c, \omega_i, t) = \mathbf{H}_m(\mathbf{r}-\mathbf{r}_c, \theta_c, t) - (\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c, \theta_c, t)\cdot\mathbf{e}_n(\mathbf{r}, \omega_i))\mathbf{e}_n(\mathbf{r}, \omega_i),\ i = 1, \ldots, N_{ns}. \tag{34}$$

The reason for which the angular frequency ω_i is contained as a variable of the projective component is to explicitly point out that the projective component is dependent on the angular frequency ω_i, where $i = 1, 2, \ldots, N_{ns}$. A roper time interval T_{test}, which consists of N_{test} durations $T_{t,k}$, where $k = 1, 2, \ldots, N_{test}$, each having a short time length Δt, is chosen, and the variation of the projective component vector $H_m^P(r - r_c, \theta_c, \omega_i, t)$ for each duration $T_{t,k}$, where $k = 1, 2, \ldots, N_{test}$, is evaluated (S86). Assume, here, that each duration $T_{t,k}$, where $k = 1, 2, \ldots, N_{test}$ does not overlap other durations. Concretely, a variance of N_{test} statistics $v_{eval,k}(\omega_i)$ of the N_{test}, where $k = 1, \ldots, N_{test}$, which are calculated by any one of the methods described below, is calculated.

(1) One or both of the means of absolute values of two orthogonal components by

$$v_{\mathrm{eval},\,k}(\omega_i) = \langle |H_{m,\,q}{}^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_c, \theta_c, \omega_i, t)| \rangle_{T_{t,k}},\ q = 1, 2;\ k = 1, \ldots, N_{test};\ i = 1, \ldots, N_{ns}. \tag{35}$$

where $\langle\cdot\rangle_{T_{t,k}}$ represents the mean value in the duration $T_{t,k}$ and $v_{eval,k}$ is a statistic calculated for the duration $T_{t,k}$.

(2) Mean of absolute values

$$v_{\mathrm{eval},\,k}(\omega_i) = \langle |\mathbf{H}_m{}^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_c, \theta_c, \omega_i, t)| \rangle_{T_{t,k}},\ k = 1, \ldots, N_{test};\ i = 1, \ldots, N_{ns}. \tag{36}$$

(3) One or both of the means of squares of two orthogonal components by

$$v_{\mathrm{eval},\,k}(\omega_i) = \langle (H_{m,\,q}{}^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_c, \theta_c, \omega_i, t))^2 \rangle_{T_{t,k}},\ q = 1, 2;\ k = 1, \ldots, N_{test};\ i = 1, \ldots, N_{ns}. \tag{37}$$

(4) One or both of square roots of the means of squares of two orthogonal components by

$$v_{\mathrm{eval},\,k}(\omega_i)=\sqrt{\left\langle\left(H_{m,\,q}{}^{P}(\mathrm{r}-\mathrm{r}_c,\ \theta_c,\ \omega_i,\ t)\right)^2\right\rangle_{T_{t,\,k}}},\ q=1,\ 2;\ k=1,\ \ldots,\ N_{test};\ i=1,\ \ldots,\ N_{ns}. \quad (38)$$

For the statistics $v_{eval,k}$, where $k = 1, \ldots, N_{test}$, calculated by these equations, the following equation

$$\mathrm{var}(\omega_i)=\frac{\sqrt{\mathrm{mean}_k\left(\left(v_{\mathrm{eval},\,k}(\omega_i)-\mathrm{mean}_k\left(v_{\mathrm{eval},\,k}(\omega_i)\right)\right)^2\right)}}{\mathrm{mean}_k\left(v_{\mathrm{eval},\,k}(\omega_i)\right)},\ i=1,\ \ldots,\ N_{ns}. \quad (39)$$

is calculated to obtain (S86) a value of $\omega_{i,min}$ that is the angular frequency ω_i which minimizes $\mathrm{var}(\omega_i)$. In the above, $\mathrm{mean}_k(.)$ indicates averaging for the suffix k, that is,

$$\mathrm{mean}_k(\,.\,)=\frac{\sum_{k=1}^{N_{test}}(\,.\,)}{N_{test}}. \quad (40)$$

The magnetic field of the angular frequency $\omega_{i,min}$ derives from the noise magnetic field, and the direction of the noise magnetic field becomes a vector $e_n(r, \omega_{i,min})$.

Incidentally, the angular frequency $\omega_{i,min}$, which minimizes $\mathrm{var}(\omega_i)$, needs only to be measured at one place and need not be obtained at every place where to measure the magnetic field.

With this method, it is also possible to calculate a fluctuation in the direction of a vector $H_m{}^P(r-r_c, \theta_c, \omega_i, t)$ as well as an amplitude fluctuation given by Eq. (39) and to select the angular frequency $\omega_{i,min}$ at which the direction fluctuation becomes minimum or smaller than a predetermined value.

Incidentally, in the above description, the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ in Step 1 is a wide-band signal, and in Step 3 it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal having passed

through a band pass filter that permits the passage therethrough of only components close to the frequency of the signal magnetic field or a wide-band signal that is inhibited from the passage through the band pass filter, but the use of the signal having passed through the band pass filter increases the possibility of determining the position of the magnetic field with high reliability.

Fig. 18 shows how to select frequencies $f_1(=\omega_1/2\pi)$, $f_2(=\omega_2/2\pi)$, ..., $f_n(=(\omega_n/2\pi$, where $n=N_{ns})$, at which the frequency spectrum becomes maximum; Fig. 19 shows the flow of processing including step S91 for obtaining the candidate vector; and Figs. 20 and 21 show the flow of processing including steps S101 and S102 or steps S111 and S112 for evaluating the candidate vector and for detecting the direction of the noise magnetic field.

The frequency spectrum $H_m(\omega)$ need not always be used. That is, the signal magnetic field is periodically turned OFF/ON following a predetermined procedure; the period T_{period} is divided into equally-spaced durations; the candidate unit vector $e_n(r, t_i)$, where $i = 1, \ldots, N_{ns}$, is used in place of the candidate unit vector $e_n(r, \omega_i)$, where $i = 1, \ldots, N_{ns}$, which is calculated by Eqs. (25), (26) and (27); and thereafter, the duration that minimized the variance by Eq. (33) is calculated by the processing described above. By this, the vector $e_n(r, t_i)$ in that duration can be adopted as the direction of he noise magnetic field.

<u>(Third method)</u>

In the second method, the large-amplitude angular frequency ω_i, where $i = 1, 2, \ldots, N_s$, is selected from the absolute value $|H_m(\omega)|$ of the frequency spectrum $H_m(\omega)$, but the vector $e_n(r, \omega_{i,min})$ can be obtained as the direction of the noise magnetic field in exactly the same manner as in the case of the second method, by selecting a proper frequency band neighboring the frequency of the signal magnetic field, setting properly-spaced test frequencies free from the frequency of the signal magnetic field in the frequency band and regarding the test frequencies as the angular frequency ω_i in the second method.

As is the case with the second method, the angular frequency $\omega_{i,min}$ at

which var(ω_i) becomes minimum needs only to be obtained.

Fig. 22 shows how to select the frequencies $f_1(=\omega_1/2\pi)$, $f_2(=\omega_2/2\pi)$, ..., $f_n(=(\omega_n/2\pi$, where $n=N_{ns})$ at which the frequency spectrum becomes maximum. The flow of the subsequent processing is the same as depicted in Figs. 17, 19 and 20.

(Fourth method)

The signal magnetic field is periodically stopped under control of a predetermined procedure. For example, the signal magnetic field is periodically stopped by a predetermined time interval. Since the intensity of the magnetic field being measured decreases while the signal magnetic field is stopped, the OFF period of the signal magnetic field is identified by regarding the intensity-decreasing period essentially as the predetermined OFF period, and the direction of the magnetic field measured during the OFF period is used as the direction of the noise magnetic field. The direction of the noise magnetic field can be obtained using the same method as the first one. Fig. 23 shows how the amplitude of the measured magnetic field in this method varies with time.

(Fifth method)

The signal magnetic field is periodically stopped following a predetermined procedure. This is carried out as described below under (1) and (2).

(1) To stop the signal magnetic field on a rectangular-wave-wise:

The signal magnetic field is repeatedly turned ON and OFF with the period T_{period}, for instance.

$$\begin{aligned} s(t) &= 1, \quad t_k \le t < t_k + t_{stop}, \\ &= -1, \quad t_k + t_{stop} \le t \le t_{k+1}. \end{aligned} \tag{41}$$

and when a sequence s(t) is 1, the signal magnetic field is turned OFF, but when the sequence is −1, the signal magnetic field is turned ON. In the above,

$$t_{k+1} - t_k = T_{period}, \; k = 1, 2, 3, \ldots \tag{42}$$

(2) To stop the signal magnetic field on a pseudo-random-signal-wise

basis:

For example, when the value is "–1" in a random sequence like an M-sequence consisting of unit periods T_{unit} of the same length N_M, the signal magnetic field is turned ON, but when the value is "1," the signal magnetic field is turned OFF; and this sequence is repeated. In this case, the time average of the sequence is set to 0.

Fig. 24 shows temporal variations in the amplitude of the measured magnetic field in the case of the signal magnetic field being stopped by the method (1). Fig. 25 shows temporal variations in the amplitude of the measured magnetic field in the case of the signal magnetic field being stopped by the method (2).

Next, as depicted in Fig. 26, the correlation function between the sequence s(t) and the norm of the measured magnetic field or the absolute value of its particular component is calculated (S121, S122, S123). As the correlation function, it is possible to use any one of those calculated by

$$R(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \left|\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right| s(t-\tau)dt. \qquad (43)$$

$$R(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \sqrt{\left(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-\tau)dt. \qquad (44)$$

$$R_\alpha(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \left|H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right| s(t-\tau)dt,\ \alpha=x,y,z. \qquad (45)$$

$$R_\alpha(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \sqrt{\left(H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-\tau)dt,\ \alpha=x,y,z. \qquad (46)$$

In this case, the period for which to detect the correlation is set to an integral multiple $N_T T_{period}$ of the period T_{period}.

The OFF state of the signal magnetic field can be detected (S125) from the time $\tau=t_{sync}$ at which any one of the above correlation functions become maximum (S124). That is, a sequence $s(t-t_{sync})$, which starts at the time $\tau=t_{sync}$, is used, and when the sequence s(t) is "1," the signal magnetic field is regarded as being OFF; in this way, the ON/OFF operation of the signal magnetic field is determined.

In the thus determined signal magnetic field OFF period the direction of the measured magnetic field is detected, and the direction is regarded as the direction of the noise magnetic field (S126). When the sequence s(t) is "−1" (a second numerical value), the signal magnetic field is turned ON, and when the sequence is "1" (a first numerical value), the signal magnetic field is turned OFF; this sequence is repeated in this way.

(Sixth method)

As is the case with the fifth method, the signal magnetic field is periodically stopped under control of such a predetermined procedure as described below.

(1) To stop the signal magnetic field on a rectangular-wave-wise:

The signal magnetic field is repeatedly turned ON and OFF with the period T_{period}, for instance.

$$\begin{aligned} s(t) &= 1, \quad t_k \le t < t_k + t_{stop}. \\ &= -1, \quad t_k + t_{stop} \le t \le t_{k+1}. \end{aligned} \qquad (41)$$

and when a sequence s(t) is 1, the signal magnetic field is turned OFF, but when the sequence is −1, the signal magnetic field is turned ON. In the above,

$$t_{k+1} - t_k = T_{period}, \; k = 1, 2, 3, \dots \qquad (42)$$

(2) To stop the signal magnetic field on a pseudo-random-signal-wise basis:

For example, when the value is "−1" in a random sequence like an M-sequence consisting of unit periods T_{unit} of the same length N_M, the signal magnetic field is turned ON, but when the value is "1," the signal magnetic field is turned OFF; and this sequence is repeated.

In this case, the sequence s(t) is chosen so that it changes for each predetermined time unit Δt_{unit}. And, the time average of the sequence is "0."

Next, as depicted in Fig. 27, the correlation function between the sequence s(t) and the norm of the measured magnetic field or the absolute value of its particular component is calculated (S131, S132, S133) as in case of the fifth

method. As the correlation function, it is possible to use any one of those calculated by

$$R(\tau)=\int_{t_k}^{t_k+N_T T_{period}}\left|\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right|s(t-\tau)dt. \qquad (43)$$

$$R(\tau)=\int_{t_k}^{t_k+N_T T_{period}}\sqrt{\left(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\,s(t-\tau)dt. \qquad (44)$$

$$R_\alpha(\tau)=\int_{t_k}^{t_k+N_T T_{period}}\left|H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right|s(t-\tau)dt,\ \alpha=x,y,z. \qquad (45)$$

$$R_\alpha(\tau)=\int_{t_k}^{t_k+N_T T_{period}}\sqrt{\left(H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\,s(t-\tau)dt,\ \alpha=x,y,z. \qquad (46)$$

In this case, the period for which to detect the correlation is set to an integral multiple $N_T T_{period}$ of the period T_{period}.

In this instance, there are present, in general, plural times $\tau=t_{sync,k}$ ($k = 1, 2, \ldots, N_{sync}$) in which the correlation function becomes maximum and the maximum value exceeds a predetermined value (S134). Assume, for example, that $t_{sync,k}$, ($k = 1, 2, \ldots, N_{sync}$) is an arrangement of such times in order of time. When the correlation value between the sequence s(t) and the signal magnetic field is appropriate,

$$\Delta t_{sync,\,k}=t_{sync,\,k}-t_{sync,\,1},\quad k=2,\ \ldots,\ N_{sync}. \qquad (47)$$

is virtually an integral multiple of the time unit Δt_{unit}. Then, the average of the value resulting from the subtraction of an integral multiple $M_{sync,k}\Delta t_{unit}$ of the time unit Δt_{sync}, where $k = 2, \ldots, N_{sync,\,k}$, from $\Delta t_{sync,k}$, where $k = 2, \ldots, N_{sync}$, is calculated by

$$\delta t_{sync}=\frac{\sum_{k=2}^{N_{sync}}\left(\Delta t_{sync,\,k}-M_{sync,\,k}\Delta t_{unit}\right)}{N_{sync}-1}. \qquad (48)$$

In this case,

$$t_{sync}=t_{sync,\,1}+\delta t_{sync} \qquad (49)$$

provides the beginning of the sequence signal corresponding to the ON/OFF.

operation of the signal magnetic field.

Accordingly, the period during which the signal magnetic field is OFF can easily be set based on the sequence $s(t-t_{sync})$.

By applying the same method as the first method to the magnetic field vector $H_m(r-r_c, \theta_c, t)$ measured in this period, the direction $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ can be calculated (S138).

(Seventh method)

This method will be described below with reference to Figs. 28, 29, 30 and 31.

As is the case with the fifth method, the signal magnetic field is periodically stopped, for example, by such a procedure as described below.

(1) To stop the signal magnetic field on a rectangular-wave-wise:

The signal magnetic field is repeatedly turned ON and OFF with the period T_{period}, for instance.

$$\begin{aligned} s(t) &= 1, \quad t_k \le t < t_k + t_{stop}. \\ &= -1, \quad t_k + t_{stop} \le t \le t_{k+1}. \end{aligned} \tag{41}$$

and when a sequence s(t) is 1, the signal magnetic field is turned OFF, but when the sequence is −1, the signal magnetic field is turned ON. In the above,

$$t_{k+1} - t_k = T_{period},\ k = 1, 2, 3, \ldots \tag{42}$$

(2) To stop the signal magnetic field on a pseudo-random-signal-wise basis:

For example, when the value is "−1" in a random sequence like an M-sequence consisting of unit periods T_{unit} of the same length N_M, the signal magnetic field is turned ON, but when the value is "1," the signal magnetic field is turned OFF; and this sequence is repeated accordingly. In this case, the time average of the sequence is "0."

Next, the correlation function between the sequence s(t) and the measured magnetic field $H_m(r-r_c, \theta_c, t)$ is calculated (S141, S142, S143). The period T_{period} is divided into equally spaced N_{div} sections of a length T_{div}, and either one of the

following calculations is conducted.

$$R_\alpha(t_k) = \int_{t_k}^{t_k+T_{period}} \left| H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t) \right| s(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \qquad (50)$$

$$R_\alpha(t_k) = \int_{t_k}^{t_k+T_{period}} \sqrt{\left(H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2} s(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \qquad (51)$$

In this case, a symbol $R_\alpha(t_k)$, where α = x, y, z and k = 1, …, N_{div}, is the time correlation between an α component $H_{m,\alpha}(r-r_c, \theta_c, t)$ of the measured magnetic field $H_m(r-r_c, \theta_c, t)$ and the sequence s(t). And

$$t_k = t_0 + k \cdot T_{div},\quad k=1,\ \ldots,\ N_{div}. \qquad (52)$$

The measured magnetic field may also be correlated with the time that is an m-multiple of the period T_{period}. That is,

$$R_\alpha(t_k) = \int_{t_k}^{t_k+mT_{period}} \left| H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t) \right| S_{mp}(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \qquad (53)$$

$$R_\alpha(t_k) = \int_{t_k}^{t_k+mT_{period}} \sqrt{\left(H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2} S_{mp}(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \qquad (54)$$

In this instance, the sequence s(t) is replaced with $S_{mp}(t)$, where

$$S_{mp}(t) = S(t+T_{period})$$
$$S_{mp}(t) = s(t),\quad 0 \le t < T_{period}. \qquad (55)$$

This is followed by calculating the component $H_m^P(r-r_c, \theta_c, t_k, t)$, where k = 1, …, N_{div}, of the measured magnetic field $H_m(r-r_c, \theta_c, t)$ projected on the vector

$\mathbf{e_n(t_k)=(R_x(t_k), R_y(t_k), R_z(t_k))}$, where k = 1, …, N_{div}

formed by correlation functions $R_\alpha(t_k)$, where α = x, y, z , corresponding to the respective components x, y and z of the measured magnetic field $H_m(r-r_c, \theta_c, t)$. Here, a symbol t_k contained as a variable of the projective component indicates that the projective component depends on the variable t_k.

In this method, the vector $e_n(t_k)$ can be used as the direction of the noise magnetic field through utilization of the time t_k in which a fluctuation in the absolute value of the projective component vector $H_m(r-r_c, \theta_c, t_k, t)$, where k = 1, …, N_{div},

$$\mathrm{var}(t_k)=\frac{\sqrt{\left\langle\left(\mathbf{H}_m{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)-\left\langle\left|\mathbf{H}_m{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t\right)^2\right\rangle_t}}{\left\langle\left|\mathbf{H}_m{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t},\quad k=1,\ \ldots,\ N_{\mathrm{div}}. \qquad (56)$$

becomes minimum or smaller than a predetermined value (S145a). In the above $\langle\cdot\rangle_t$ means the calculation of the time average.

Further, variances of the x-component $H_{m,x}(r-r_c,\ \theta_c,\ t_k,\ t)$, y-component $H_{m,y}(r-r_c,\ \theta_c,\ t_k,\ t)$ and z-component $H_{m,z}(r-r_c,\ \theta_c,\ t_k,\ t)$ of the projective component vector $H_m(r-r_c,\ \theta_c,\ t_k,\ t)$, where $k=1,\ \ldots,\ N_{\mathrm{div}}$,

$$\mathrm{var}_\alpha(t_k)=\frac{\sqrt{\left\langle\left(H_{m,\alpha}{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)-\left\langle H_{m,\alpha}{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right\rangle_t\right)^2\right\rangle_t}}{\left\langle\left|\mathbf{H}_m{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t}, \qquad (57)$$

$$\alpha=x,\ y,\ z;\ k=1,\ \ldots,\ N_{\mathrm{div}}.$$

are calculated, and the vector $e_n(t_k)$ can be used as the direction of the noise magnetic field through utilization of the time t_k in which the sum of the above-mentioned variances

$$\sum_{\alpha=x,y,z}\mathrm{var}_\alpha(t_k) \qquad (58)$$

or

$$\sqrt{\sum_{\alpha=x,y,z}\left(\mathrm{var}_\alpha(t_k)\right)^2}. \qquad (59)$$

becomes minimum or smaller than a predetermined value (S145b). In this case, there is the possibility that the correlation functions $R_x(t_k)$, $R_y(t_k)$ and $R_z(t_k)$ at a certain time t_k have lost their original signs. Hence, it is necessary to evaluate the fluctuation of the projective component at each time t_k for four combinations $[R_x(t_k),\ R_y(t_k),\ R_z(t_k)]$, $[R_x(t_k),\ R_y(t_k),\ -R_z(t_k)]$, $[R_x(t_k),\ -R_y(t_k),\ R_z(t_k)]$ and $[R_x(t_k),\ -R_y(t_k),\ -R_z(t_k)]$.

Further, the period during which the signal magnetic field is OFF can easily be set (S145c, S145d) based on the sequence $s(t-t_k)$. By applying the same

method as the first one to the magnetic field vector $H_n(r-r_c, \theta_c, t)$ measured in this period, the direction $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ can be obtained (S146). In the above, use is made of the time t_k of the equally spaced N_{div} sections of a the time length T_{div} divided from the period T_{period}, but it is also possible to use the time when the correlation function given by Eq. (45) or (46) becomes maximum or when the correlation function becomes maximum and exceeds a predetermined value.

(Method for determining the direction of the noise magnetic field when the number of noise magnetic fields is virtually two)

Even in a case of two noise magnetic fields, when a first one of the two noise magnetic fields has far higher an intensity than the second noise magnetic field at a first frequency and the second noise magnetic field has far higher an intensity than the first noise magnetic field at the second frequency, the directions of the first and second noise magnetic field can easily be calculated through utilization of these frequency components in the measured magnetic field.

If the first or second frequency is close to the frequency of the signal magnetic field, the directions of the noise magnetic fields can be determined from the measured magnetic field having passed through a band pass filter that permits the passage therethrough of only frequencies near those of the signal magnetic field, by the same method as the fourth or fifth method for use in the case of virtually one noise magnetic field.

When either of the first and second frequencies does not equal to the frequency of the signal magnetic field, the directions of the respective noise magnetic fields need only to be calculated by the same method as the first one for use in the case of virtually one noise magnetic field.

(Other embodiments)

The present invention is also effective when the signal magnetic field generated by the magnetic field source is virtually axially symmetric, and the invention permits position determination with a smaller number of magnetic

sensors or by magnetic field sensing at a smaller number of positions than in the case of a magnetic field of low symmetry.

Further, when only one noise magnetic field affects the measurement of the digging position and the tilt angle of the magnetic field source is known which is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, the projective component of the magnetic field, measured at each of two or more different positions, on a plane perpendicular to the direction of the noise magnetic field sensed at each of the magnetic field sensing positions is calculated; the position of the magnetic field source and its azimuth angle that is the direction of the axis of symmetry in a horizontal plane can be calculated from the above-said projective component.

Further, according to this invention method, when virtually one noise magnetic field affects the measurement of the digging position, the projective component of the magnetic field, measured at each of three or more different positions, on a plane perpendicular to the direction of the noise magnetic field sensed at each of the magnetic field sensing positions is calculated; the position of the magnetic field source, its tilt angle that is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, and the azimuth angle of the magnetic field source that is he direction of the axis of symmetry in the horizontal plane can be calculated from the above-said projective component.

Further, when virtually two noise magnetic fields alone affect the measurement of the digging position and the tilt angle of the magnetic field source is known which is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, the projective component of the magnetic field, measured at each of four or more different positions, on a straight line perpendicular to both of the direction of a first one of the two noise magnetic fields sensed at each

magnetic field sensing position and the direction of the remaining second noise magnetic field sensed at the same position is calculated; the position of the magnetic field source and its azimuth angle that is the direction of the axis of symmetry in the horizontal plane can be calculated from the above-said projective component.

Further, when virtually two noise magnetic fields alone affect the measurement of the digging position, the projective component of the magnetic field, measured at each of five or more different positions, on a straight line perpendicular to both of the direction of a first one of the two noise magnetic fields sensed at each magnetic field sensing position and the direction of the remaining second noise magnetic field sensed at the same position is calculated; the position of the magnetic field source, its tilt angle that is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, and the azimuth angle that is the direction of the axis of symmetry in the horizontal plane can be calculated from the above-said projective component.

Moreover, when virtually two noise magnetic fields alone affect the measurement of the digging position, the frequency component of a first one of the two noise magnetic fields, in the vicinity of which the remaining second noise magnetic field and the signal magnetic field have substantially no frequency components, is measured to thereby permit detection of the direction of the first noise magnetic field in terms of vector; and the frequency component of the second noise magnetic fields, in the vicinity of which the first noise magnetic field and the signal magnetic field have substantially no frequency components, is measured to thereby permit detection of the direction of the second noise magnetic field in terms of vector.

In the present invention, it is effective to use, as a magnetic sensor, a three-axis magnetic sensor that senses three magnetic fields orthogonal to one another at substantially the same position.

The magnetic sensor for use in the present invention may be any kinds of sensors as long as they are capable to three magnetic fields orthogonal to one another at substantially the same position, but the three-axis magnetic sensor is suitable which senses three magnetic fields orthogonal to one another at substantially the same position. Alternatively, it is possible that one magnetic sensor capable of sensing a magnetic field in only one direction is turned at the same position toward three orthogonal directions one after another to sense the three orthogonal magnetic fields.

In carrying out the present invention, it is possible to employ such a frame 12 as depicted in Fig. 32 which has magnetic sensor fixing means 11 mounted thereon to fix three-axis magnetic sensors and a tilt angle gauge 13 for detecting the inclination of the frame with respect to a vertical direction. The position of each magnetic sensor fixing means on the frame is known, and the magnetic sensor fixing means possesses a function of fixing the magnetic sensor in a predetermined orientation to the frame. The magnetic sensor fixing means 11 is provided with, for example, three faces orthogonal to one another, and has a mechanism that fixes the magnetic sensor at a predetermined angle when a predetermined face of the sensor case is pressed against any one of the three faces of the sensor fixing means. One magnetic sensor or one three-axis magnetic sensor is fixed to these magnetic sensor fixing means one after another to sense the magnetic fields.

In another alternative, a plurality of magnetic sensors may be fixed in predetermined orientations to the frame 12 at a plurality of positions to simultaneously sense magnetic fields at the plurality of positions.

As described above, the present invention employs a frame provided with a plurality of magnetic sensor fixing means each capable of removably or fixedly mounting a three-axis magnetic sensor and a tilt angle sensor capable of detecting the tilt angle of an orthogonal coordinate system to the vertical direction, the magnetic fixing means being mounted on the frame so that their positions and orientations are known; the magnetic sensor is removably or fixedly mounted on a

required number of magnetic sensor fixing means to sense magnetic fields, and the tilt angle of the frame during magnetic field sensing and the orientation of the magnetic sensor at each magnetic sensor mounting position with respect to the frame are used to calculate from the magnetic field sensed at each magnetic sensor mounting position the sensed magnetic field, a noise magnetic field and a signal magnetic field as vectors in a coordinate system fixed to the ground.

The magnetic field generating means for the signal magnetic field in the present invention may be a coil. The magnetic field generating means may be one electric wire as well, or may also be one electric wire that is straight only in the vicinity of the place of position determination.

As described above, even if a buried power line, railroad tracks, or similar noise magnetic sources are present near a construction site, the present invention permits highly reliable position determination without being affected by noise magnetic fields generated by such noise magnetic field sources.

The present invention is intended for measuring the digging position in the non-open-cut method of excavation, but is applicable as well to many technical fields that involve position determination by sensing magnetic fields.